RECOGNIZING DEFECTS IN CARBON-FIBER REINFORCED PLASTICS

R. Schuetze and W. Hillger

Translation of "Erkennbarkeit von Fehlern in CFK-Laminaten", Deutsche Gesellschaft fuer Luft- und Raumfahrt, Jahrestagung, Aachen, West Germany, DGLR Paper 81-057, May 11-14, 1981, pp 1-20

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16. Abstract

The damage tolerance of structures made of carbon-fiber-reinforced plastic is tested under various loads. Test laminate (73/1/1, 24/9/1, 1465 A) specimens of thickness 1.5-3.2 mm with various defects were subjected to static and dynamic loads. Special attention was given to delamination, and ultrasonic C-scans were made on the specimens. It was shown that cracks from even small defects can be detected with great accuracy. The same probes were also X-rayed; defects that could not be detected under ordinary X-rays were bored and studied under vacuum by a contrast technique. The nondestructive ultrasonic and X-ray tests were controlled by partially destructive tests, and good agreement was observed between the two.

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Recognizing Defects in Carbon-Fiber Reinforced Plastics

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1. INTRODUCTION

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The use of carbon-fiber-reinforced plastics (CFP) for highly stressed structural parts in airplane construction depends to a decisive degree on how the quality of the material can be guaranteed. Not all defects which arise during the fabrication or during later operation of the airplane necessarily lead to a replacement of the structural part. Rather, one must make sure that existing flaws do not affect the strength behavior of the structural part and that, if they progress further, a timely replacement can be made.

This damage tolerance in structural parts assumes that, in addition to a reliable non-destructive testing, timely predictions can be made concerning the growth of such flaws during further operation [1]. While such predictions can be made quite reliably for metallic materials, considerable gaps in knowledge exist for fiber resin composites.

It is the task of fracture mechanics to investigate the behavior of defective CFP-laminates under various stress conditions in order to thus determine the mechanism of the flaw propagation. In these investigations non-destructive testing takes on great importance since the spreading , or the growth of defects can be determined only with suitable test methods.

With the aid of test laminates having different defects, the accuracy, magnitude and shape of even very small defects in CFP-laminates can be proven with the aid of the ultrasonic (US)--and X-ray technology using non-destructive methods. Finally, the high measuring accuracy of the US-testing is utilized in order to observe the propagation of defects in CFP samples under stress.

*Numbers in margin indicate pagination of foreign text

2. TEST LAMINATES

The recognizability of defects was established with CFP-laminates having different internal defect locations (Figure 1) [2].

The sample 73/1/1 (column 2, Figure 1) contains a delamination which was generated with an encapsulated inflating agent. During the preparation of the laminate, a certain number of microcapsules, which were filled with liquid freon, was applied between two prepreg layers. During the resin curing process, the freon leaked out of the capsule, evaporated and produced a delamination. The residue of the microcapsules which at the time still contain some freon remain in the laminate and could be seen in the X-ray picture.

The laminate 24/9/1 (column 3, Figure 1) contained delaminations and bubbles which resulted from over-curing. After the usual curing process (180°C, one hour) the laminates were post-cured for four hours at a temperature of 220°C. This produced bubbles of different size and depth in the laminate.

While the above named samples were produced in-house, the sample 1465A was made available by the Dornier GmbH Co., Friedrichshafen. The laminate had a thickness of 3.2 mm and contained fiber voids of different sizes which had spread at times in the direction of the fibers for the corresponding layer.

To investigate the defect, propagation samples and compression samples were prepared (column 5, Figure 1). Each sample contained, always in the center and in the center plane of the laminate, a delamination introduced in a defined manner. The delaminations were produced by a heat resistant, double layer separating foil with a total thickness of 0.05 mm. Assurance was provided during the laminate fabrication that there was no adhesion between the foils. /57-2

3. TEST EQUIPMENT AND MEASUREMENT CAPABILITIES

The tests were made with a high resolution US-installation and with an X-ray apparatus particularly suitable for CFP. Both apparatuses will be described briefly.

3.1 Ultrasonic testing system

Figure 2 shows the electronics of the US-testing systems [3] housed in a 19" cabinet.

In the upper slide-in unit we find the coordinate control device (in-house development) for the step-motor driven X-Y-manipulator (Figure 3) which moves the test head in a meandering fashion over the sample. The step width was 0.042 mm. As a special feature, the control device contains two coordinate systems whereby one describes the field segment (scanning range). By changing the connections in the digital-analog-converter in the apparatus, plots of 1 : 100 to 100 : 1 can be recorded. For both coordinate systems, two six-place digital displays are provided which display the position of the test head continuously (Figure 2). Before the start of the automated scan programs, the initial and final values, as well as the line spacing, must be entered.

The third slide-in unit from above (Figure 2) contains the US-test apparatus, Echograph 1054, with built-in signal monitor and the narrow-band transmitter 1140.68. (Both apparatuses from the Karl Deutsch Co.).

The narrow-band transmitter makes possible a step-free selection of the testing frequency (1 to 10 MHz) when one and the same transducer test head is used.

The US-evaluation unit (in-house development) in the second slide-in unit contained an additional signal monitor for monitoring the surface echo of the sample. In addition, digital and analog

signal connections whose outlets are placed on a programming field are also provided. By means of simple connections of wire jumpers, C-scans and amplitude plots (even perspective ones) can be recorded optionally with the fast X-Y recorder (HP 7045A) located on the bottom in the 19" cabinet. Since the edge of the sample is marked by the interruption of the scan lines during the recorder plots, the C-scan provides direct information concerning the location of the defects.

The fourth slide-in unit contains an additional monitor so that, with the aid of an additional X-Y plotter, two C-scans with different defect levels can be recorded simultaneously.

Since the CFP laminates exhibit considerably higher sound-attenuation coefficients than homogeneous metals, a test head adaptation was developed. It is also located in the fourth slide-in unit and provides a signal/noise ratio spacing higher by about 6-8 dB.

For defect depth measurements, we used a 100 MHZ memory oscilloscope (Tektronics 466). With it, it is possible to spread the US-HF signals in the sample domain to such an extent that, with the aid of the echo intervals, the defect depths can be determined point-by-point. /57-3

The US testing was done by means of sound penetration. We evaluated for the relatively thin laminates not only the defect echo, but also the echo of an auxiliary reflector (glass plate) which was located at a small distance from the sample. Breaks in the US-amplitude of 6-24 dB, depending on sample quality, lead to a deflect display.

The test frequency was 10 MHz for all US investigations. We were able to use this relatively high test frequency for CFP since the maximum sample thickness was only 3.2 mm and because of the additional impedance adaptation of the test head to the narrow-band transmitter, a signal/noise separation of more than 30 dB resulted.

In order to achieve a defect resolution as high as possible, extensive sound-field tests were made before the tests with the focus test head used (Krautkrämer H 10 MP 15). The defect resolution was increased through the selection of a small scan-line distance of 0.16 mm in conjunction with an enlarged result plotting scale of 5 : 1.

3.2 X-ray equipment

For the X-ray recordings, we used a modified full-protection Philips Co. type MUJ X-ray apparatus. The X-ray tube (MCN 161) has a small focus of 0.4 x 0.4 mm and thereby makes possible a high X-ray picture resolution. The X-ray energy can be selected within the range of 10 KeV-100KeV and is thus well-suited for CFP material.

To increase the contrast of the X-ray pictures, we used the contrast agent tetrabromethane (TBE). This test capability will be discussed in more detail later [4].

4. RESULTS OF THE TESTING OF THE TEST LAMINATES

4.1 Laminate 73/1/1

The US-testing of the sample 73/1/1 was conducted with three different sensitivities (Figure 4). The recorded defects of the three C-scans resulted at trigger levels of 24 dB, 18 dB and 12 dB (amplitude breaks which were greater than the indicated trigger levels led to defect recordings). Here the distinct differences in the sizes of the defect were noted.

Because of increased porosity in the vicinity of the defect, the edge of the artificial delamination became indistinct. This blurred edge, which also shows in the X-ray picture of the contrasted sample, affects to a high degree the defect size, as recorded by the US-apparatus at different sensitivities. The sound attenuation of a single small pore is too small for a defect indication.

However, accumulations of pores attentuate the sound to such an extent that, depending on the sensitivity chosen, the defect areas of different sizes are indicated. The C-scans of the sample 73/1/1 clearly point out this condition. These same defective areas are marked in the X-ray picture through increased penetration of contrast agents.

For contrasting studies, the sample was immersed in tetrabromethane (TBE) before the X-ray test. Even those voids in the laminate which resulted from inflating agents in the vicinity of the defect were able to completely suck up the contrast agent under vacuum and thus were easily visible in the X-ray picture because of the strong /57-4 absorption capability of TBE. The comparison of an X-ray picture of the non-contrasting sample (Figure 5) shows especially well which details can be recognized additionally by the contrast agent.

4.2 Laminate 24/9/1

In contrast to sample 73/1/1, the C-scan of sample 24/9/1 (Figure 6) shows three relatively clearly outlined defects whose sizes were also confirmed to a large extent by the other test methods. The defects (lenticular -shaped cavities) could be easily found by means of US-testing and it was shown that the determination of the defect edges depended less on the setting of the sensitivity of the US-apparatus than for sample 73/1/1.

The fact that the defect edges were not blurred by pores is also shown by the X-ray picture of the contrasting sample. The three clearly visible delaminations (bubbles) could not readily be confirmed in the TBE-immersion bath since there were no connections to the cutting edges through which the contrast agent might have been able to penetrate. Therefore, the bubbles were drilled in accordance with the previously made US-C-scan and were contrasted individually under a vacuum bell jar.

The drilling of defects with subsequent contrasting and X-ray testing can be considered as a quasi-nondestructive test method.

Here the hole diameters must be selected sufficiently small so that the strength behavior of the sample or a structural part is not affected. Hole diameters of 0.1 mm are sufficient to allow the contrasting agent to penetrate. After the X-ray pictures have been taken, the contrasting agent can be readily vaporized quickly from the laminate under vacuum.

After X-ray testing, sample 24/9/1 was cut into 45 0.2 mm thick slices whose cross-sections were measured under the microscope. The result is shown in Figure 6.

4.3 Laminate 1465A

Figure 7 shows C-scan and X-ray picture of the sample 1465A. The 3.2 mm thick laminate contains voids of different sizes and position. The sometimes very voluminous voids can be easily recognized in the X-ray picture even without contrasting. X-ray picture section and C-scan exhibit the same sample area and are shown to the same scale. A comparison of both representations shows how accurately even very small voids can be depicted with the aid of the high-resolution US testing system.

With the aid of the C-scan, individual voids were again tested by the test head and the US echoes arising at the voids were represented with the aid of a 100 MHz memory oscilloscope (Figure 8). In this way, the void depth, as shown by two examples, can be determined very accurately.

5. ULTRASONIC INVESTIGATIONS OF THE DEFECT PROPAGATION OF CFP-SAMPLES WITH DELAMINATIONS UNDER OSCILLATING STRESSES

The good detailed recognizability obtained with the US-method was used to observe the propagation of defects in CFP samples under stress. Particular attention had to be paid to the reproducibility of the measurements. For that reason, high stability of all elec- /57-5 tronic and mechanical adjustments, including the positioning of the

sample were stressed. To prepare the samples for defect propagation investigations, elastomeric seal materials were bonded to the cutting edges in order to prevent the penetration of water into the defect locations for defects spreading from the edge. Because of sound coupling, penetrated water would inhibit recognition of existing defects.

Figure 9 shows C-scans of different stress stages of a sample during a static tensile test. After the stress stages, which are always indicated below the C-scans had been attained. the sample was unclamped from the testing machine and was tested by the US-method.

As can be clearly seen, changes showed up only at the sample edge. We are dealing here with delamination in the 90° layers which grew into the sample starting from the edge as the result of peeling stresses. Expectedly, an enlargement of the artificial delamination could not be noticed. A remarkable phenomenon at the C-scans is the sample edge marking even for delaminated edges. This representation becomes possible by an appropriate arrangement of the signal monitors of surface and defect (reflector) echoes.

Figure 10 shows C-scans of a sample which was stressed in a static pressure test. Above 700 N/mm^2 we were able to notice a spreading of the artificial delamination as the result of buckling of the separated layers. After the first crack, small increases in stress are sufficient to produce a distinct spreading of the delamination. Since no peeling stresses arise in this stress case at the edge of the sample, no edge delaminations developed either. To determine the size of the defect, we used an electrical counter during this test. The counter summed up all the motor steps which are classified as defects by the US-apparatus. In this way, the defect propagation can be more quantitatively described.

C-scans of samples under dynamic loading are shown in Figure 11. Since the sample was stressed in tension and pressure ($R = -1$, $\sigma = 400\ N/mm^2$), the spreading of the delamination from the

edge as well as the enlargement of the artificial delamination in the center of the sample can be observed. The first changes of the sample were found after 5000 stress cycles.

With the aid of the series of C-scans, it can be determined that even small changes of a defect propagation can be recognized with the aid of the high-resolution US-test system.

6. SUMMARY

In order to investigate the recognizability of interior defects in CFP-laminates, samples with thicknesses of 1.5 to 3.2 mm and different defect types were tested. Special attention was paid to delamination.

Of all the samples, we first prepared ultrasound (US) C-scans with sound penetration technology. These measurements were made with a high-resolution US-test installation.

It was found that outlines of even very small defects could be defined with great accuracy. Details of the equipment, their measuring potentials and of the measurements conducted are described in greater detail.

In addition to US-investigations, we also conducted X-ray /57-6 tests with the same samples. Interior defects which could not be recognized in a simple X-ray picture were drilled and were treated, under vacuum, with a contrasting agent so that the defects showed up clearly in subsequent X-ray pictures. This quasi-nondestructive test method assumes that the hole diameters for drilling selected do not affect the strength behavior of the structural part.

Some US and X-ray tests were checked with destructive testing. A good agreement was found between the nondestructive and the destructive tests.

The good detail recognizability attained especially with the US-method was utilized to investigate the propagation of defects in stressed CFP samples during defect-mechanical investigations. For this purpose, tension and compression samples with delaminations were stressed statically and dynamically and the propagation of defects was observed after a certain number of load steps or stress cycles.

7. REFERENCES

[1] E. A. B deGraaf, P. deRijk, G. F. J. A. van Jostel. Supplementary damage tolerance proof of an airplane landing gear structural part after numerous starts and landings. Materialpruefung (Material Testing) 22 (1980) no. 9.

[2] R. Schuetze, W. Hillger, H. Bauml. Zerstoerungsfreie Pruefung duenner CFK-Laminate mit innenliegenden Fehlern (Non-destruction testing of thin CFP laminates with interior defects), DFVLR, IB 152-80/13 (1980).

[3] W. Hillger. Entwicklung und Bau einer Ultraschallpraezisionspruefanlage zur Messung des Schadensfortschrittes in CFK-Proben (Development and construction of an ultrasonic position testing installation for the measurement of the defect propagation in CFP samples), DFVLR, IB 152-80/14.

[4] F. H. Chang, D. E. Gordon, B. T. Rodini, R. H. McDaniel. J. Composite Materials, Vol. 10 (July 1976), p. 182.

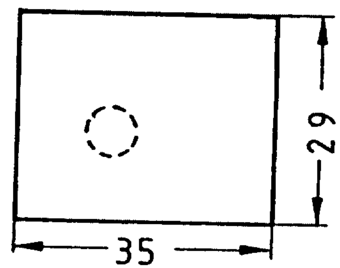
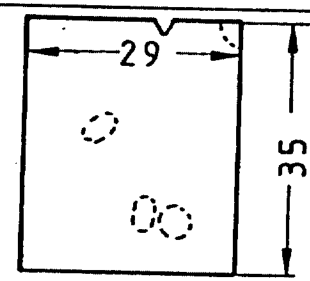
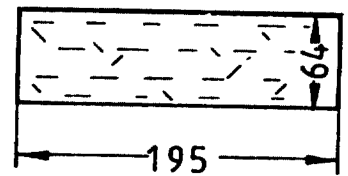
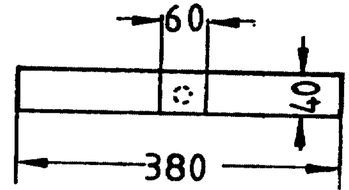
Laminate	73/1/1	24/9/1	1465 A (Dornier)	214/1 214/6 214/7
Dimensions [mm]				
Thickness [mm]	1,5	1,5	3,2	2
Material	T 300/914 C	T 300/914 C	?	T 300/914 C
Layer buildup	$[0^\circ_2, +45^\circ, -45^\circ, 90^\circ_2]_s$	$[0^\circ_2, +45^\circ, -45^\circ, 90^\circ]_s$	?	$[0^\circ_2, +45^\circ, 0^\circ_2, -45^\circ, 0^\circ, 90^\circ]_s$
Defect type	delamination (inflating agent)	delamination (excess hardening)	fiber void in fiber direction	delamination (foil)

Figure 1. Test objects.

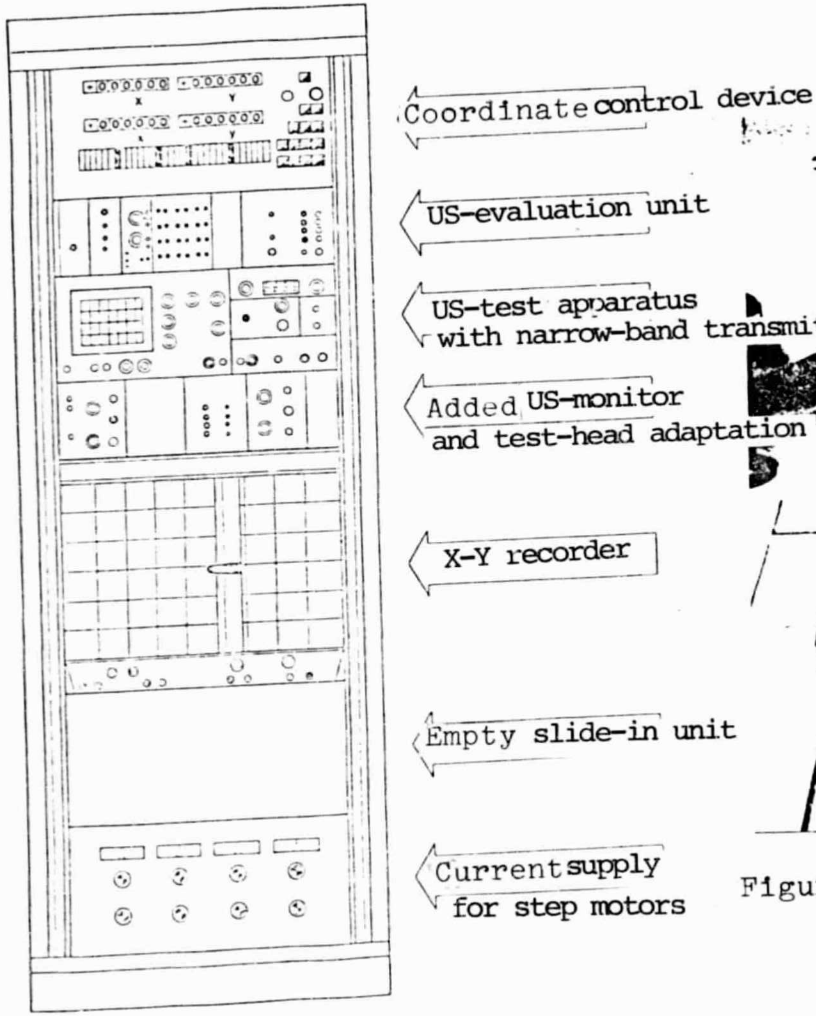


Figure 2. Electronics of the ultrasonic equipment.

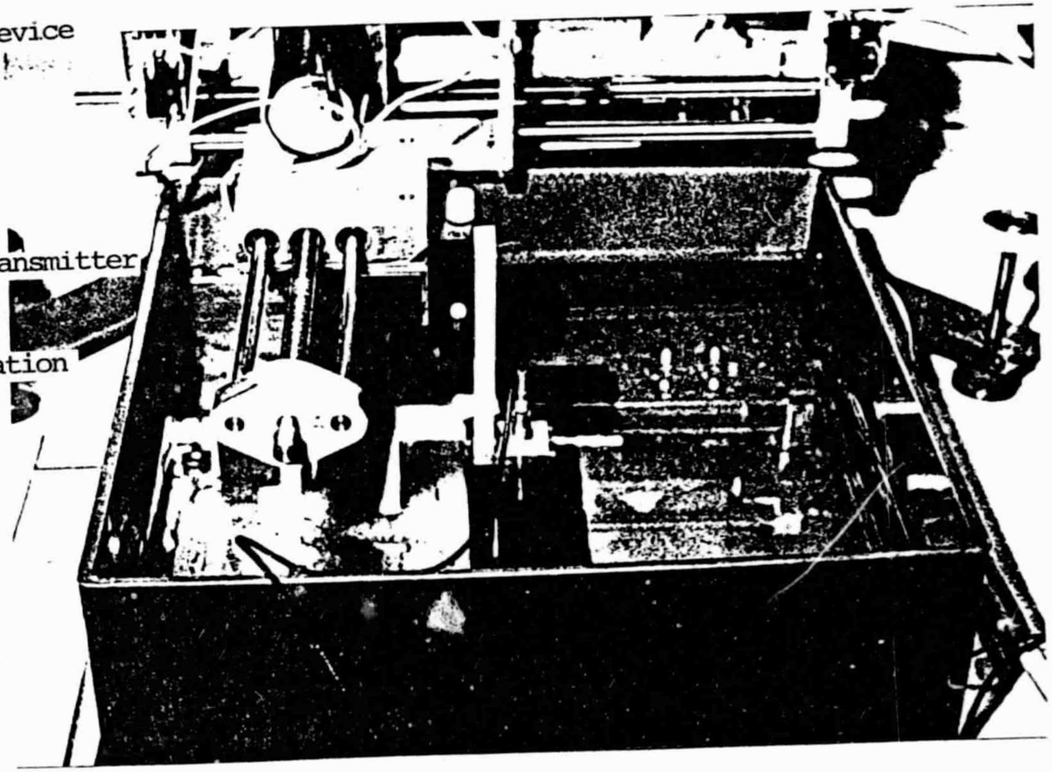
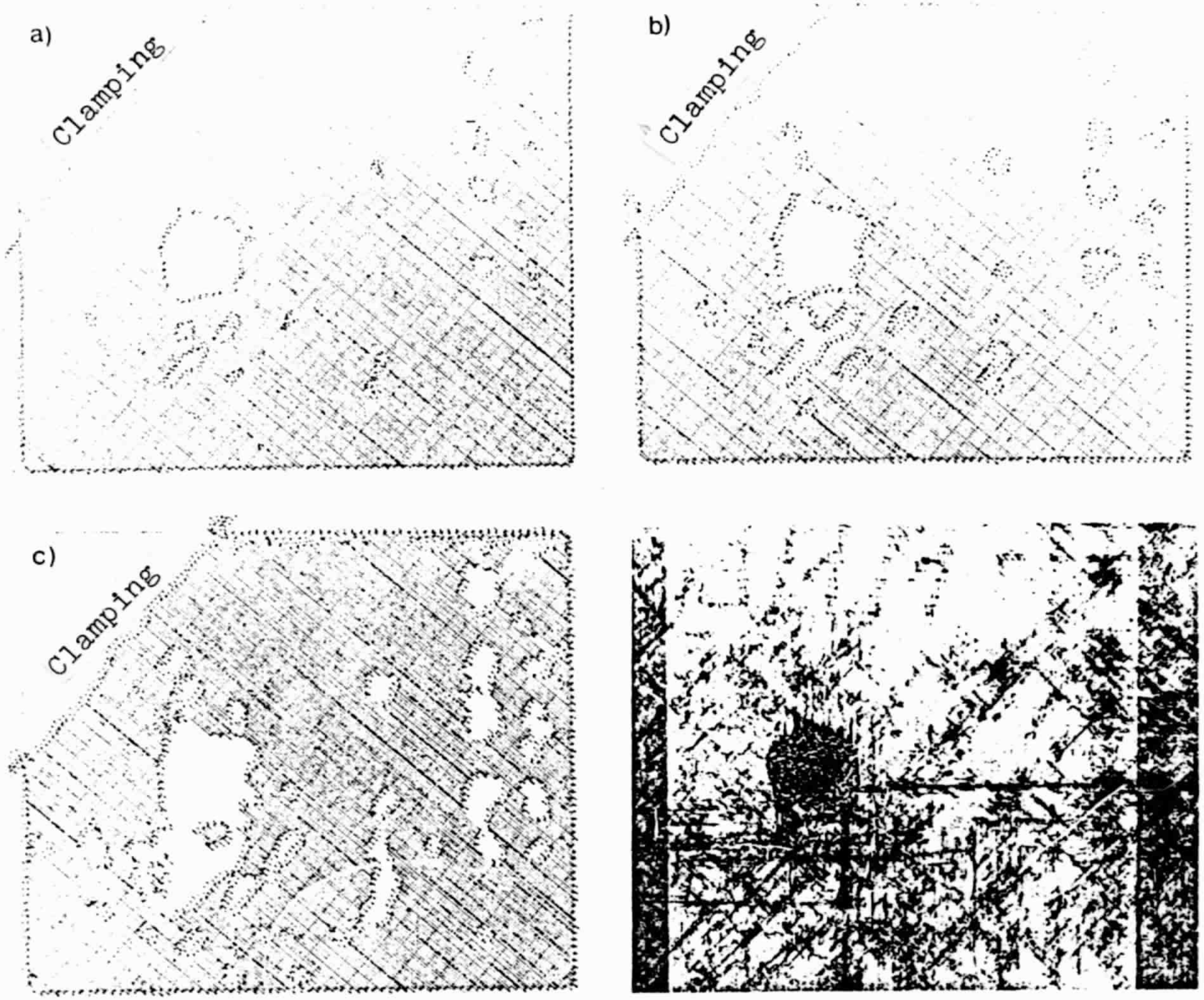


Figure 3. X/Y-manipulator of the ultrasonic installation.



Laminate 73/1/1 Laminate thickness 1,5 mm test frequency: 10 MHz

Sensitivities : a) 24 dB, b) 18 dB, c) 12 dB — Amplitude break of the auxiliary Reflector echo, compare 3.1

X-ray energy: 10 keV
Illumination time: 40 s
Contrasting agent: TBE

Figure 4. C-scans and x-ray picture of the sample 73/1/1.

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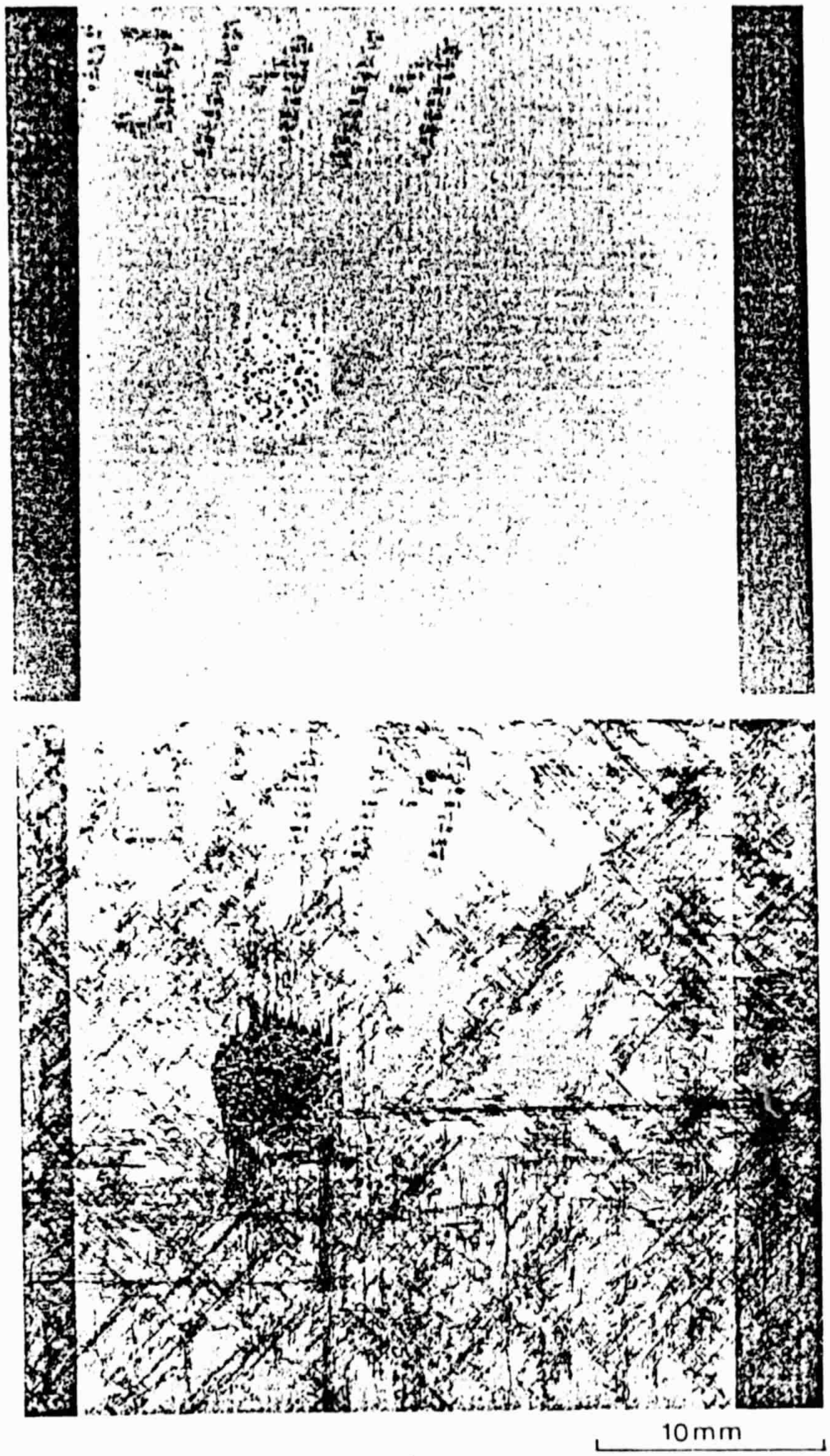
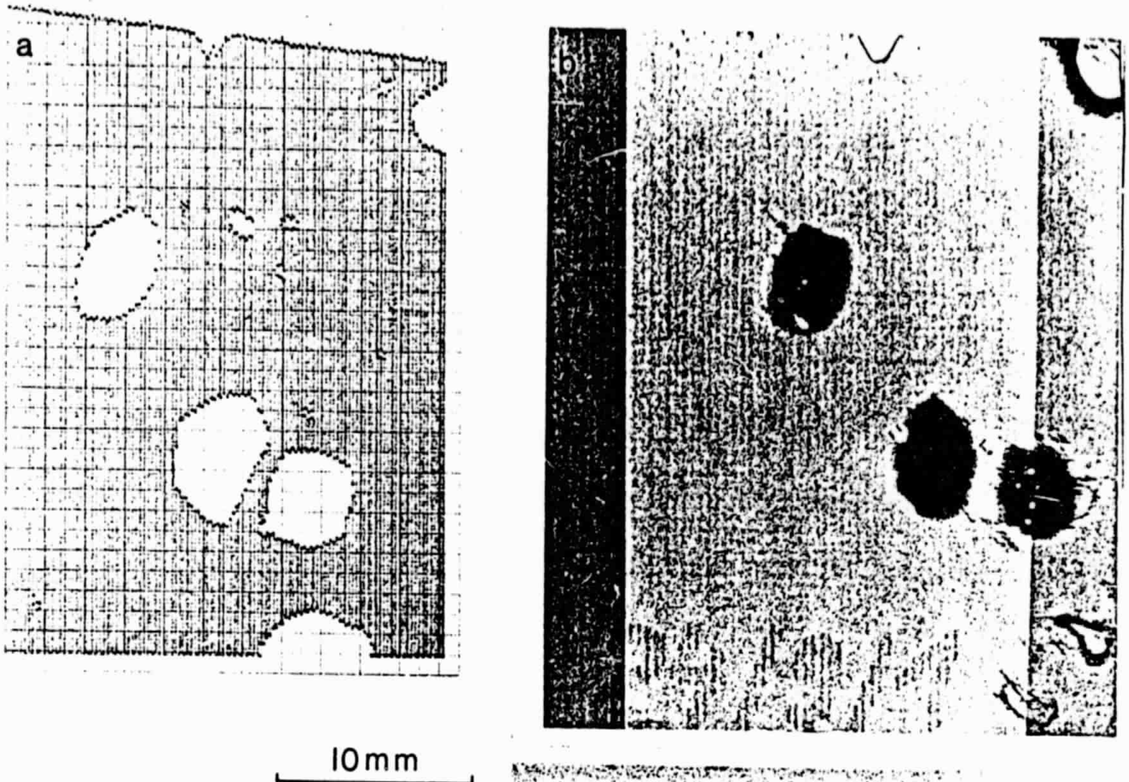


Laminate 73/1/1 Laminate thickness: 1.5 mm

X-ray energy : 10 keV Contrasting agent : TBE

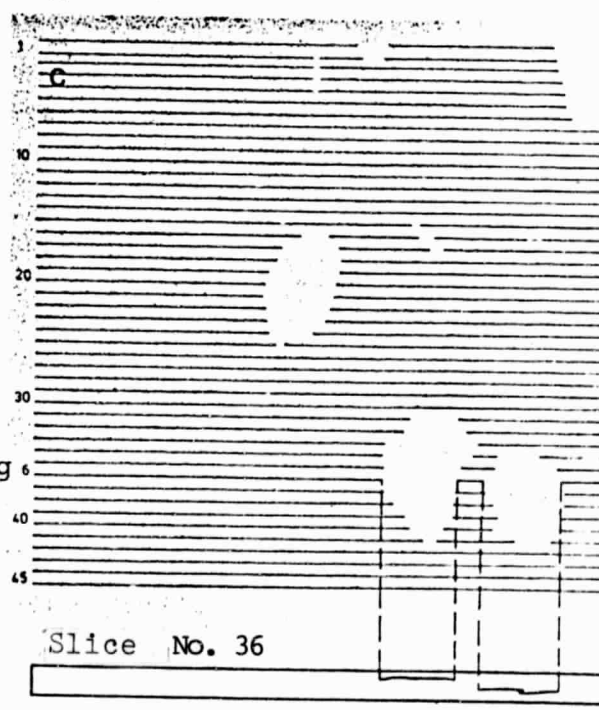
Illumination time : 40 s

Figure 5. X-ray pictures of the sample 73/1/1 (with and without contrasting agent).



Laminate 24/9/1

Laminate thickness : 1,5 mm

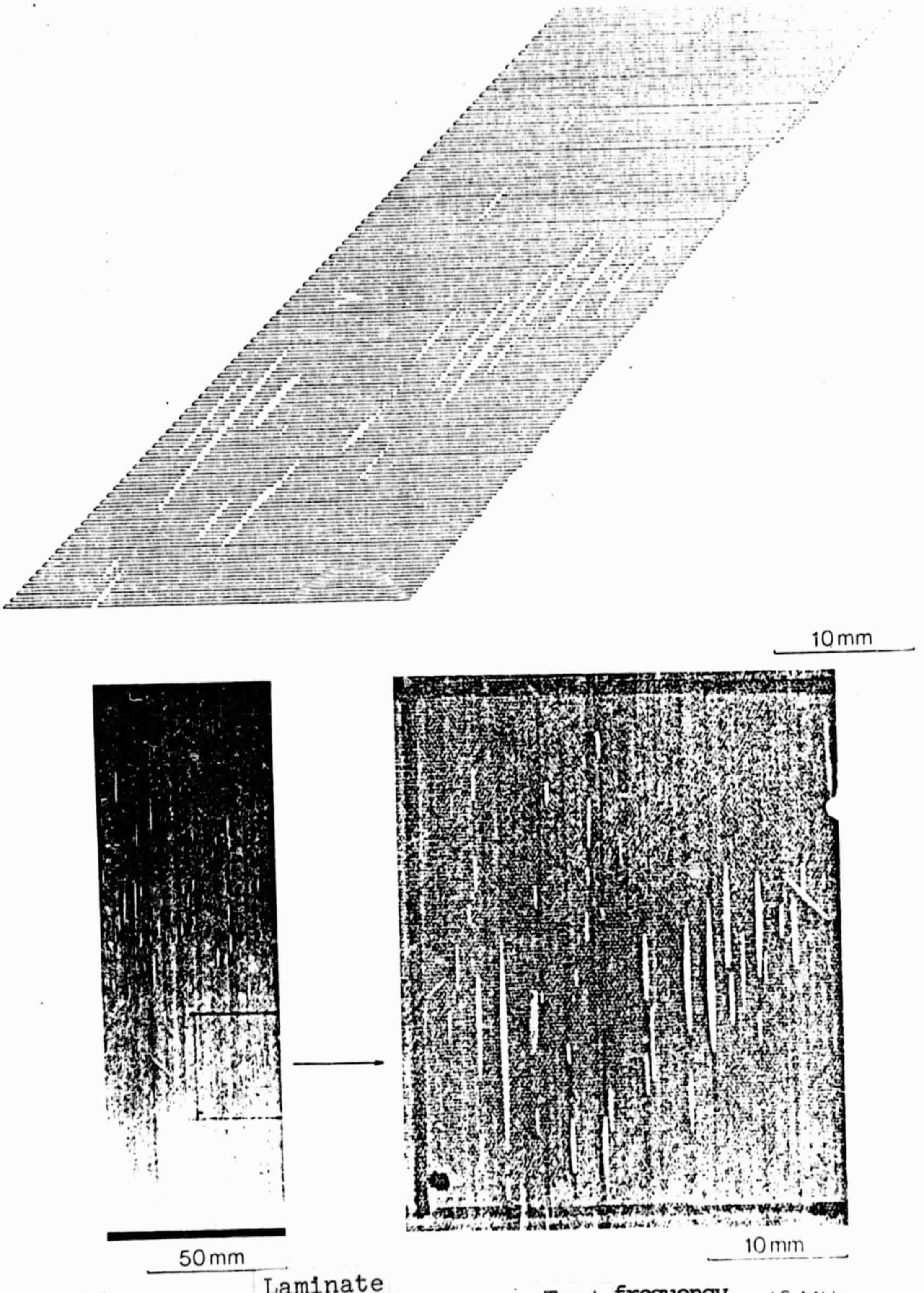


a) US-C-scan: 10 MHz
focus test head

b) X-ray picture of the contrasting sample
X-ray energy : 10 keV
Illumination time : 40 s

c) Evaluation of the destructive test

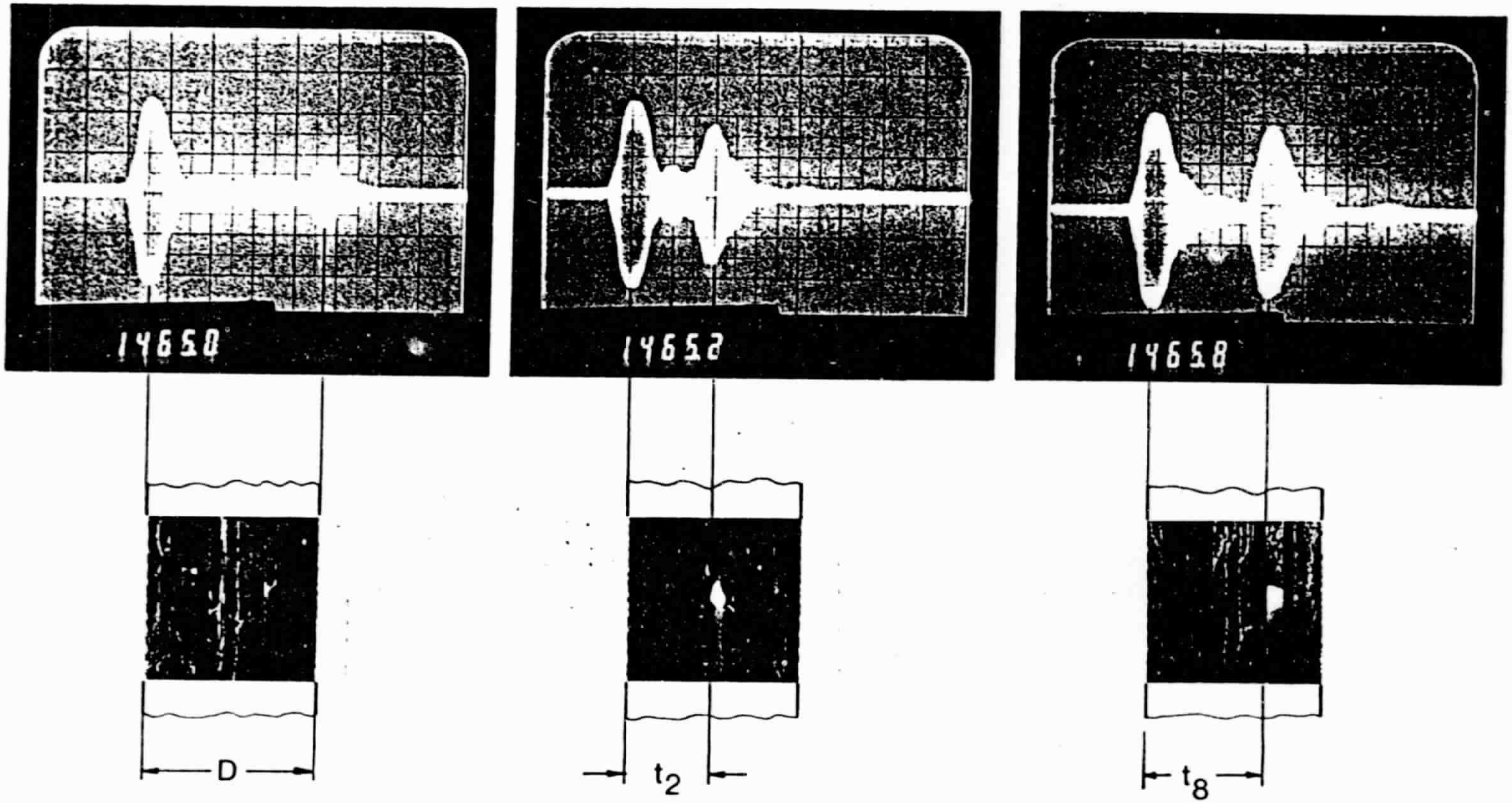
Figure 6. C-scan, X-ray picture and evaluation of the destructive test of the sample 24/9/1.



Laminate 1465A   Laminate thickness : 3,2 mm   Test frequency : 10 MHz

X-ray energy : 15 keV   Illumination time : 30 s

Figure 7. C-scan and x-ray picture of the sample 1465 A.



D=3,2 mm Laminate thickness

t_2= 1,49 mm (Ultrasound)
t_2= 1,52 mm (Microscope)

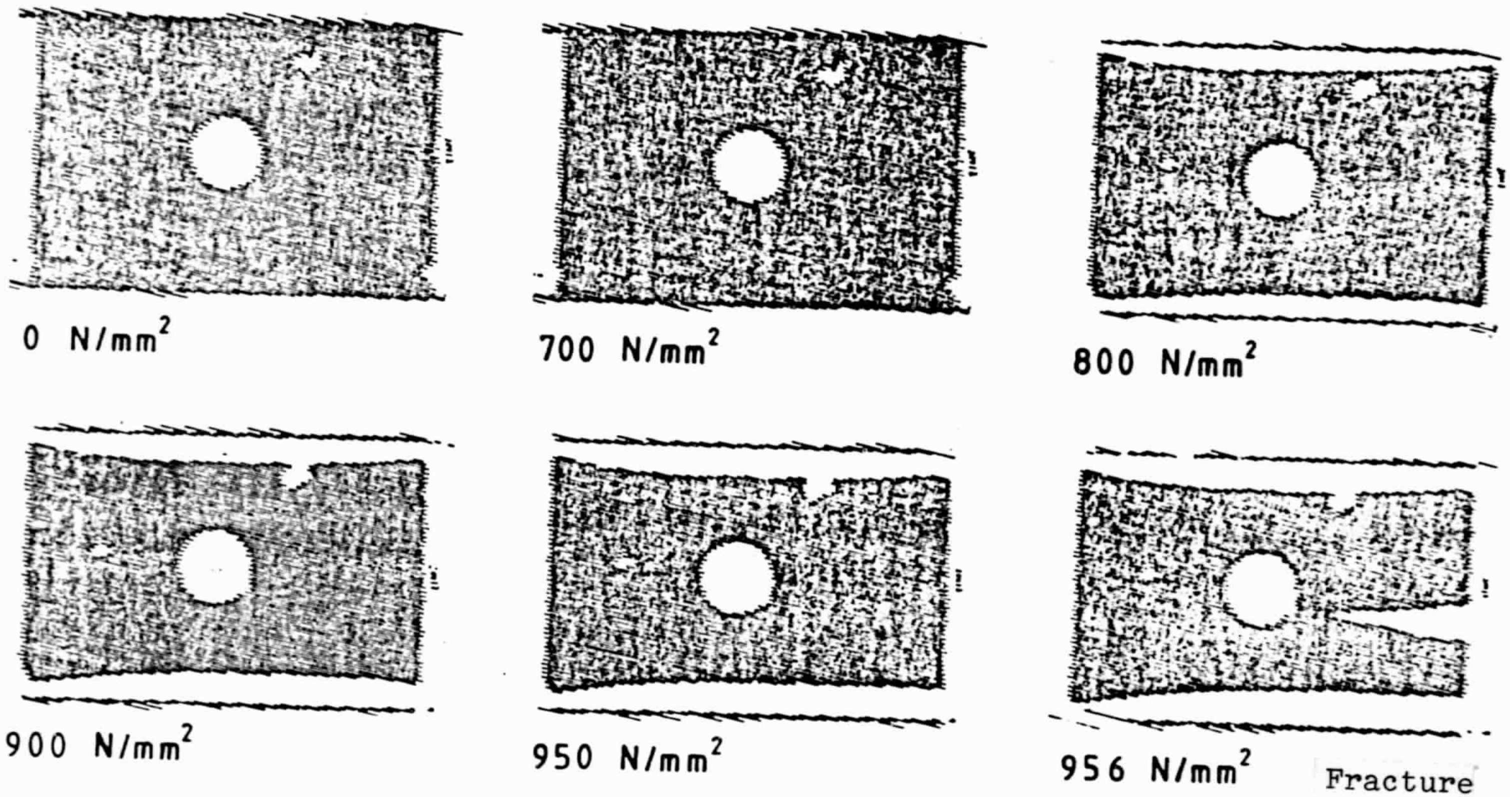
t_8 = 2,18 mm (Ultrasonic)
t_8 = 2,18 mm (Microscope)

Laminate 1465 A

Test frequency : 10 MHz

Test head : H10 MP15

Figure 8. Ultrasonic defect depth measurement at two fiber voids of the sample 1465 A.

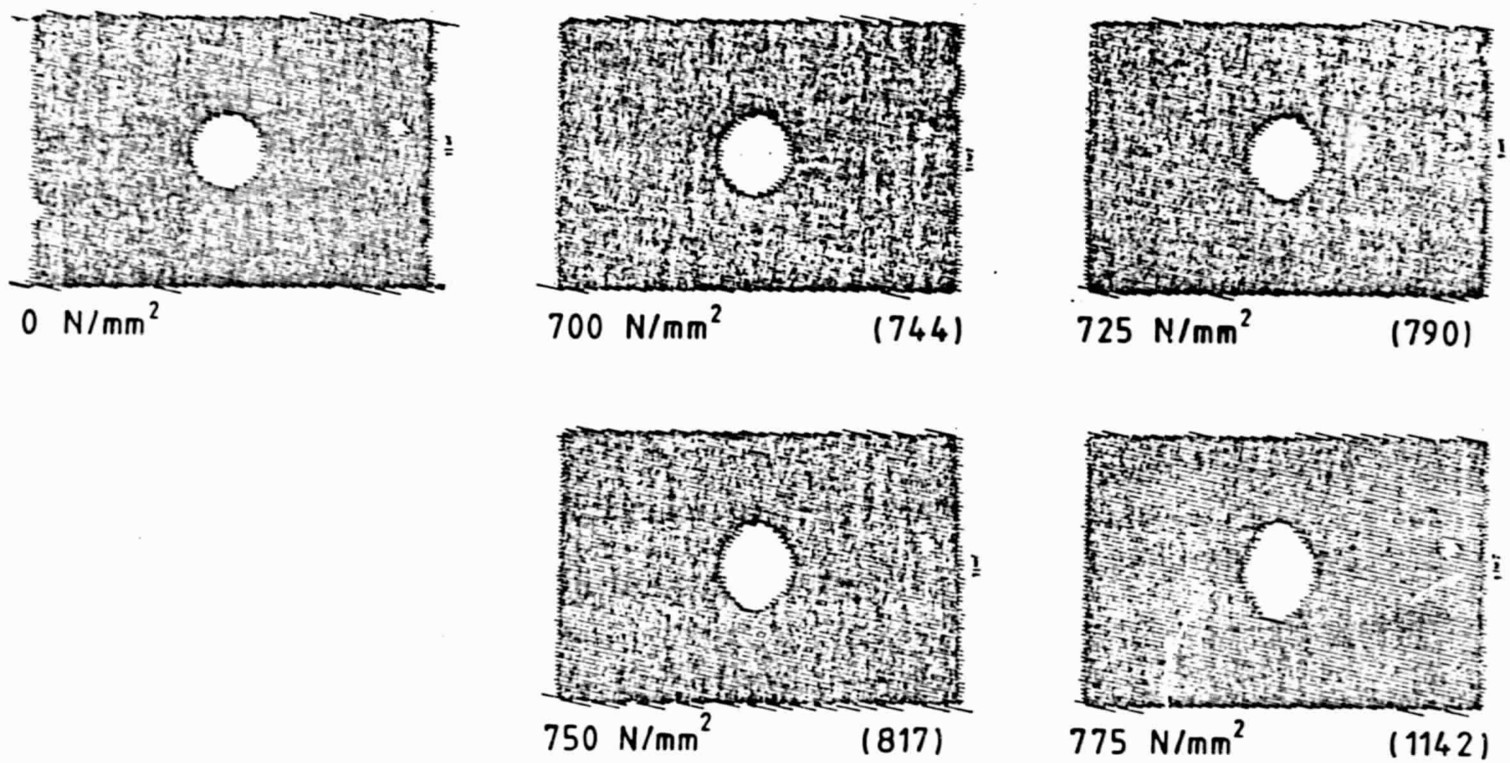


CFP-sample 214/7 thickness : 2 mm

Layer buildup : $[0^\circ_2, +45^\circ, 0^\circ_2, -45^\circ, 0^\circ, 90^\circ]_s$

Delamination in center plane- static tensile stress

Figure 9. Ultrasonic measurements of the defect propagation of a CFP-sample with delamination under static tensile stress.



CFP-sample 214/6 Thickness : 2 mm

Layer buildup : $[0^\circ_2, +45^\circ, 0^\circ_2, -45^\circ, 0^\circ, 90^\circ]_s$

Delamination in center plane- static tensile stress

Figure 10. Ultrasonic measurements of the defect propagation of a CFP-sample with delamination under static tensile stress.

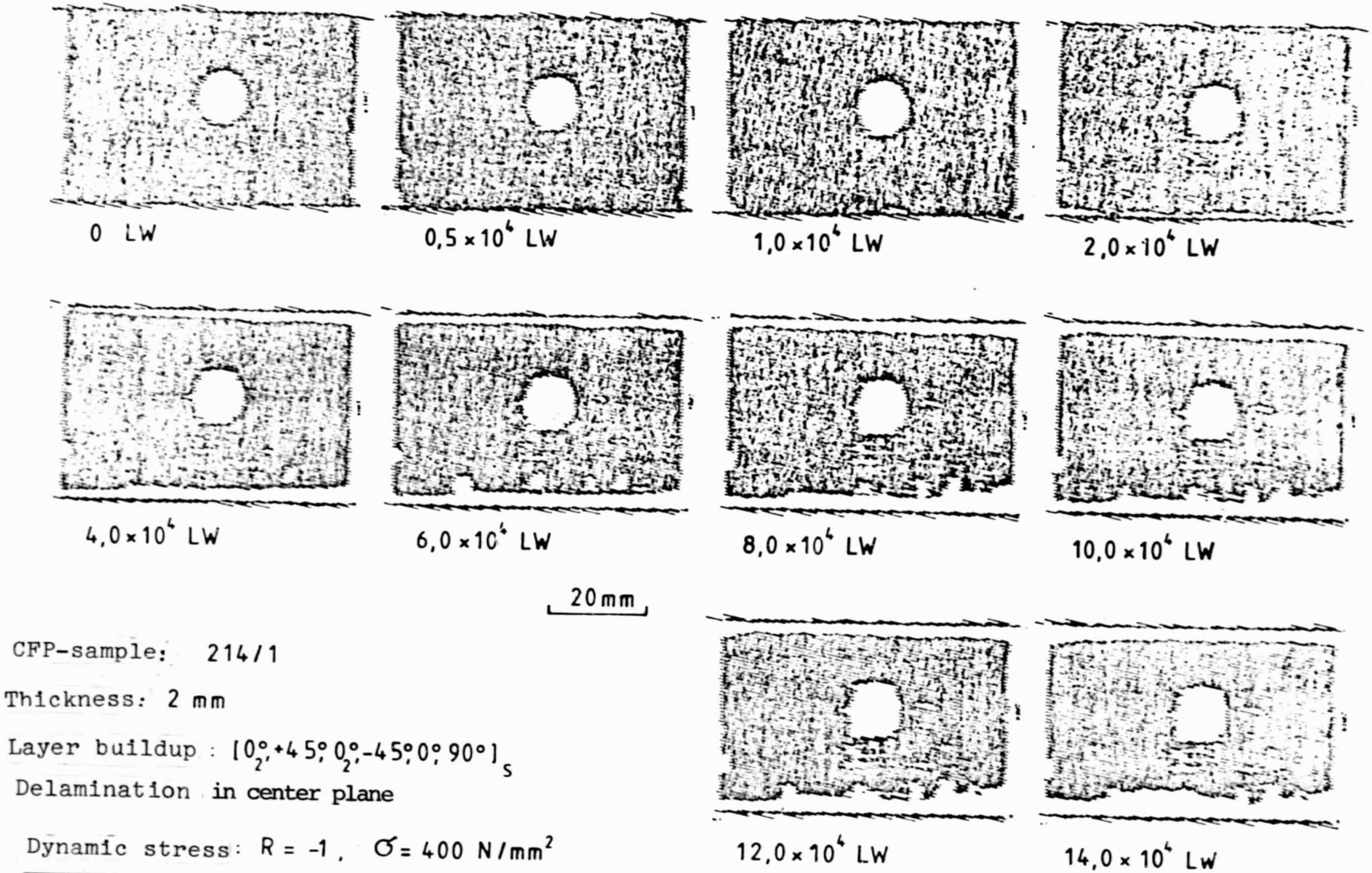


Figure 11. Ultrasonic measurements of the defect propagation of a CFP-sample with delamination under cyclic stress.